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ON THE NATURE OF THE X(3872)

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We present recent studies of charmonium multi-quark states. We use different interacting models and numerical methods to study deeply bound four-quark states and meson-meson molecules. No deeply bound four-quark states are found in our analysis. A nice description of the X(3872) is obtained as a $D\bar{D}^* - J/\Psi\omega$ coupled channel state.

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Since 2003 several states have been discovered in the charmonium mass region. While in the conventional description of charmonium in terms of quark-antiquark pairs some states are still missing, the number of experimental states reported up to now is larger than empty spaces in the $c\bar{c}$ spectrum. This overpopulation, together with other difficulties to explain observed states as simple quark-antiquark pairs, triggered discussions¹ on a possible exotic interpretation, four-quark states either as compact tetraquarks or slightly bound meson-meson molecules.

Understanding of charmonium spectroscopy is challenging for experimentalists and theorists alike. Charmonium has been used as the test bed to demonstrate the color Fermi-Breit structure of quark atoms obeying the same principles as ordinary atoms². Its nonrelativistic character gave rise to an amazing agreement between experiment and simple quark potential model predictions as $c\bar{c}$ states³. The opening of charmed meson thresholds was expected to modify the trend in the construction of quark-antiquark models. In the adiabatic approximation meson loops were absorbed into the static interquark potential. Thus, close to the threshold production of charmed mesons models required of an improved interaction⁴.

The discussion above suggests that charmonium spectroscopy could be rather simple below the threshold production of charmed mesons but much more complex

above it. In particular, the coupling to the closest $(c\bar{c})(n\bar{n})$ system, referred to as *unquenching the naive quark model*⁵, could be an important spectroscopic ingredient. Therefore, hidden-charm four-quark states could explain the overpopulation of quark-antiquark theoretical states. Thus, the new experimental discoveries are offering exciting new insights into the subtleties of the strong interaction.

In an attempt to disentangle the role played by multiquark configurations in the charmonium spectroscopy we obtained an exact solution of the four-body problem based on an infinite expansion of the four-quark wave function in terms of hyperspherical harmonics⁶. From our analysis, we concluded that those four-quark states with two different asymptotic physical thresholds (as it is the case of the $c\bar{c}n\bar{n}$ system that may split either into a $(c\bar{c})(n\bar{n})$ or $(c\bar{n})(n\bar{c})$ two-meson states) can hardly present a bound state since the interaction between any pair of quarks contributes to the energy of one of the two physical thresholds. Close to a threshold we have used a different technique that we developed when studying baryon spectra with screened potentials. We solved the Lippmann-Schwinger equation looking for attractive channels that may contain a meson-meson molecule⁷. In order to account for all basis states we allow for the coupling to charmonium-light two-meson systems. Thus, we consider the system of two mesons M_1 and \bar{M}_2 ($M_i = D, D^*$) in a relative S -state interacting through a potential V that contains a tensor force, and therefore there is a coupling to the $M_1\bar{M}_2$ D -wave. Moreover, the two D -meson system can couple to a charmonium-light two-meson state, for example $D\bar{D}^*$ is coupled to $J/\Psi\omega$. We have consistently used the same interacting Hamiltonian to study the two- and four-quark systems to guarantee that thresholds and possible bound states are eigenstates of the same Hamiltonian.

Table 1. Attractive channels for the two D -meson systems.

| System | $D\bar{D}$ | $D\bar{D}^*$ | $D^*\bar{D}^*$ | | |
|-------------|-------------|--------------|----------------|-------------|-------------|
| $J^{PC}(I)$ | $0^{++}(0)$ | $1^{++}(0)$ | $0^{++}(0)$ | $2^{++}(0)$ | $2^{++}(1)$ |

Our results are shown in Table 1. This study has been the first systematic analysis of four-quark hidden-charm states as compact states or meson-meson molecules. For the first time we have performed a consistent study of all quantum numbers within the same model. Our predictions robustly show that no deeply bound states can be expected for this system. Only a few channels can be expected to present observable resonances or slightly bound states. Among them, we have found that the $D\bar{D}^*$ system must show a bound state slightly below the threshold for charmed mesons production with quantum numbers $J^{PC}(I) = 1^{++}(0)$, that could correspond to the widely discussed $X(3872)$. Of the systems made of a particle and its corresponding antiparticle, $D\bar{D}$ and $D^*\bar{D}^*$, the $J^{PC}(I) = 0^{++}(0)$ is attractive. It would be the only candidate to accommodate a wide resonance for the $D\bar{D}$ system. For the $D^*\bar{D}^*$ the attraction is stronger and structures may be observed close

and above the charmed meson production threshold. Also, we have shown that the $J^{PC}(I) = 2^{++}(0, 1)$ $D^*\bar{D}^*$ channels are attractive due to the coupling to the $J/\Psi\omega$ and $J/\Psi\rho$ channels, respectively.

Among these exotic theoretical states, charged states have an unique feature: by construction they cannot be accommodated into the conventional $c\bar{c}$ spectrum. Two different experimental findings show positive results on charge charmonium mesons. The first one was a $\Psi(2S)\pi^+$ peak at about 4430 MeV/c² observed by Belle in the $\bar{B}^0 \rightarrow \Psi(2S)\pi^+K^-$ decays⁸. A second positive observation was reported by Belle from the $B^0 \rightarrow \Xi_{c1}\pi^+K^-$ decay, with two resonances in $\Xi_{c1}\pi^+$ at masses of about 4050 and 4250 MeV/c²⁹. In the first case, BaBar has presented its own analysis¹⁰ performing a detailed study of the acceptance and possible reflections concluding that no significant signal exists on the data. While the two experiments made different conclusion, the data itself seem to be in a reasonable agreement except for the lower available statistics of the BaBar experiment. The states found in Ref.⁹ could correspond to the $D^*\bar{D}^*$ $J^{PC}(I) = 2^{++}(1)$ we have predicted⁷. Its confirmation would represent a unique tool in discriminating among different theoretical models.

Due to heavy quark symmetry, replacing the charm quarks by bottom quarks decreases the kinetic energy without significantly changing the potential energy. In consequence, four-quark bottomonium mesons must also exist and have larger binding energies. An experimental effort in this direction will confirm or rule out the theoretical expectations. If the scenario presented here turns out to be correct, it will open a new interesting spectroscopic area.

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